An effective soil–structure interaction consideration approach for time domain simulations of offshore wind turbines

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7. GIGAWIND Symposium, 2 March 2017, Leibniz Universität Hannover
Motivation

Transient dynamics of offshore wind turbines implies multiple impacts

- Control & Electrical System
- Aerodynamics
- Structural Dynamics
- Hydrodynamics
- Soil Dynamics
State-of-the-art: Soil-structure interaction modeling methods

Improved two-step soil-structure interaction modeling method

Results and verification of the approach
State of the art

State-of-the-art soil-structure interaction modeling methods:

- Clamped structure
- Apparent fixity length
- Uncoupled springs
- Coupled springs
- p-y-curves
- FEM/BEM soil models

Do we need to add additional DOFs for more accuracy?
State-of-the-art: Soil-structure interaction modeling methods

Improved two-step soil-structure interaction modeling method

Results and verification of the approach

\[ \sum F = ma \]
Modelling of the substructure (in FAST)

Multi-member substructure

\[ \Phi = \begin{pmatrix} I & 0 \\ \Phi_R & \Phi_L \end{pmatrix} \]

"Remove" base nodes

\[ u_{Base} = 0 \]

Linear FE representation

\[ \dot{u} + B \ddot{u} + Ku = F \]

Craig-Bampton reduction (\( K \) is singular due to rigid body motion)
Modelling of the substructure (new approach)

Multi-member substructure

Linear FE representation (add equivalent soil matrices)

\[(M + M_{\text{Soil}})\ddot{u} + B\dot{u} + (K + K_{\text{Soil}})u = F\]

\[\Phi^* = \begin{pmatrix} I & 0 \\ \Phi_R^* & \Phi_L^* \end{pmatrix}\]

Craig-Bampton reduction (\(K + K_{\text{Soil}}\) is NOT singular)

\[u_{\text{Base}} \neq 0\]

„Keep“ base nodes and consider soil properties
Derivation of soil matrices (piles)

Determine operating point

Model the foundation (below substructure) in FE solver, e.g. pile structure with p-\( \gamma \)- and T-\( z \)-curves

\[
K_{\text{Soil}} = \begin{pmatrix}
k_x & \cdots & k_{x\psi} \\
\vdots & \ddots & \vdots \\
k_{\psi x} & \cdots & k_{\psi}
\end{pmatrix}
\]

Reduce the inertial and elastic properties to the uppermost point (interface between pile and substructure), e.g. by Guyan Reduction

Method to obtain soil matrices is arbitrary!
Determination of operating point

Soil stiffness depends on acting loads

Determination of the operating point can be relevant

Time domain simulations to estimate the loads are too time consuming. Piecewise polynomial approximations on the basis of environmental conditions are acceptably exact.
1. State-of-the-art: Soil-structure interaction modeling methods

2. Improved two-step soil-structure interaction modeling method

3. Results and verification of the approach

\[ \sum F = ma \]
Comparisons of results

Substructure: OC3 Monopile (NREL 5MW)

<table>
<thead>
<tr>
<th>DLC</th>
<th>DOF's</th>
<th>Wind</th>
<th>Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>Substructure, Tower</td>
<td>$\rho_{\text{Air}} = 0 \text{ kg/m}^3$</td>
<td>Irregular</td>
</tr>
</tbody>
</table>
| 5.2 | All               | Turbulent
  $v_{\text{hub}} = 11.4 \text{ m/s}$
  $I_{\text{ref}} = 0.14$
|          |                    | Irregular
  $H_s = 6 \text{ m}$
  $T_p = 10 \text{ s}$ |

Soil-structure interaction methods:

- Clamped structure
- Apparent fixity length
- New approach
- Comparison results (OC3)
Comparisons of results (Monopile)

DLC 4.2 (Substructure and tower DOF's, $\rho_{\text{Air}} = 0 \text{ kg/m}^3$, Irregular waves)

![Graph showing comparisons of results](image)

- **Clamped structure**
- **Apparent fixity length**
- **New approach**
- **Comparison results (OC3)**

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Comparisons of results (Monopile)

DLC 5.2 (All DOF's, Turbulent wind, Irregular waves)

- Clamped structure
- Apparent fixity length
- New approach
- Comparison results (OC3)
New results for jacket substructures

Substructure: OC4 Jacket (NREL 5MW)

Load case:

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</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>Substructure, Tower</td>
<td>$\rho_{\text{Air}} = 0 \text{ kg/m}^3$</td>
<td>Irregular</td>
</tr>
<tr>
<td>5.7</td>
<td>All</td>
<td>Turbulent</td>
<td>Irregular</td>
</tr>
</tbody>
</table>

$v_{\text{hub}} = 18 \text{ m/s}$  
$I_{\text{ref}} = 0.14$

Clamped structure

--- Apparent fixity length

--- New approach (pile)

--- New approach (suction bucket)

--- pile diameter = 6x leg diameter

--- operating point: initial loads
New results for jacket substructures

DLC 5.7 (All DOF's, Turbulent wind, Irregular waves)

- Clamped structure
- Apparent fixity length
- New approach (pile)
- New approach (bucket)
Operating point and soil model results
Comparison of different lateral soil models (p-y-curves) with and without operating point consideration

- Thieken with load consideration
- Thieken with initial loads
- API with load consideration
Conclusion

- Soil-structure interaction is substantial for time domain simulations.

- State-of-the-art approaches are either too inaccurate or too numerically expensive.

- New approach improves the accuracy without adding DOFs to the substructure.

- The approach is very flexible.

- Soil models and operating point have to be chosen with care.
Thank you for your attention!

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References


